

The Fall and the Rise of X-rays from Dwarf Novae in Outburst: *RXTE* Observations of VW Hyi and WW Ceti

D. Fertig¹, K. Mukai², T. Nelson^{3,4}, and J.K. Cannizzo⁵

*Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle,
Baltimore, MD 21250.*

ABSTRACT

In a dwarf nova, the accretion disk around the white dwarf is a source of ultraviolet, optical, and infrared photons, but is never hot enough to emit X-rays. Observed X-rays instead originate from the boundary layer between the disk and the white dwarf. As the disk switches between quiescence and outburst states, the 2–10 keV X-ray flux is usually seen to be anti-correlated with the optical brightness. Here we present *RXTE* monitoring observations of two dwarf novae, VW Hyi and WW Ceti, confirming the optical/X-ray anti-correlation in these two systems. However, we do not detect any episodes of increased hard X-ray flux on the rise (out of two possible chances for WW Ceti) or the decline (two for WW Ceti and one for VW Hyi) from outburst, attributes that are clearly established in SS Cyg. The addition of these data to the existing literature establishes the fact that the behavior of SS Cyg is the exception, rather than the archetype as is often assumed. We speculate on the origin of the diversity of behaviors exhibited by dwarf novae, focusing on the role played by the white dwarf mass.

Subject headings: Stars

¹Present address: Department of Physics & Astronomy, George Mason University, MSN 3F3, Fairfax, VA 22030

²Also CRESST and X-ray Astrophysics Laboratory, NASA/GSFC, Greenbelt, MD 20771

³Also X-ray Astrophysics Laboratory, NASA/GSFC, Greenbelt, MD 20771

⁴Present address: School of Physics and Astronomy, University of Minnesota, 116 Church St. SE, Minneapolis, MN 55455

⁵Also CRESST and Astroparticle Physics Laboratory, NASA/GSFC, Greenbelt, MD 20771

1. Introduction

The outburst cycles of dwarf novae are understood as due to thermal instability in the accretion disk around the white dwarf primary. In the simplest form of the theory, the disk traces an S-curve in the surface density (Σ)–effective temperature (T_{eff}) plane, with two stable branches. The mass transfer rate from the Roche-lobe filling secondary is sufficiently low in dwarf novae that the disk is usually in the quiescent branch in which T_{eff} is low and hydrogen is mostly neutral. The disk is completely out of steady state, with accretion rate \dot{m} at each radius r varying as $\dot{m}(r) \propto r^3$, so the accretion rate onto the white dwarf is low and Σ increases over time. When it reaches the end of the quiescent branch, the disk jumps to the outburst branch in which the disk is hot, ionized, and efficiently transports matter onto the white dwarf. See Lasota (2001) for a comprehensive review of the disk instability theory.

Dwarf novae are well known sources of 2–10 keV X-rays, particularly during quiescence but also in outburst. Since the accretion disk surrounding a white dwarf is never hot enough to generate X-rays, even during outburst, we must seek their origin elsewhere. A widely held view is that they originate in an equatorial boundary (Patterson & Raymond 1985a,b), which connects the Keplerian accretion disk to the slowly rotating white dwarf surface. The detection of a narrow X-ray eclipse in OY Car (e.g., Wheatley & West 2003) and other deeply eclipsing dwarf novae in quiescence is consistent with this picture, while casting doubt on the “coronal siphon flow” model of Meyer & Meyer-Hofmeister (1994), which posits a hot, spatially extended X-ray emitting region around the white dwarf. In the rest of this paper, we therefore proceed with the boundary layer model as the basis of our interpretation.

In this view, the quiescent boundary layer is optically thin and hot ($kT \sim 10$ keV) while the outburst boundary layer is predominantly optically thick with ($kT \sim 10$ eV) but also contains an optically thin region. Coordinated multi-wavelength observations of dwarf novae can therefore reveal the physical states of the accretion disk and the boundary layer, at different points during the outburst cycle. Previous campaigns during a single outburst include those on SS Cyg (Wheatley et al. 2003), VW Hyi (Wheatley et al. 1996; Hartmann et al. 1999), and GW Lib (Byckling et al. 2009). These three campaigns in particular had dense enough X-ray coverage through the outburst to enable the authors to study the time evolution of X-ray flux. Campaigns that covered multiple outburst cycles include those on YZ Cnc (Verbunt et al. 1999), V1159 Ori (Szkody et al. 1999), and SU UMa (Collins & Wheatley 2010). Here we present our analysis of two sets of X-ray observations taken with the PCA instrument (Jahoda et al. 1996) on board *RXTE* (Bradt et al. 1993), one of a superoutburst of VW Hyi, the other of WW Cet obtained over three months and containing two outbursts. These data sets are well suited to the study of transitions of the X-ray emissions

from quiescence to outburst and back.

2. Observations and Data Reduction

VW Hyi is a dwarf nova with a quiescent magnitude of $V \sim 14$ and an orbital period of 1.78 hr (Schoembs & Vogt 1981). In addition to the normal outbursts (once every 20–30 d), it has superoutbursts once every 180 d or so, the defining characteristic of the SU UMa subclass. The superoutbursts are brighter ($V \sim 8.5$ vs. 9.5) and last longer (10–14 d vs. 3–5 d), and are characterized by superhumps, which are photometric variations at a period slightly longer than the orbital period (~ 1.84 hr). Smith et al. (2006) estimated its white dwarf to be $0.71^{+0.18}_{-0.26} M_{\odot}$ based on a refined measurement of the gravitational redshift in the photospheric absorption line. Pringle et al. (1987) contains further details of VW Hyi.

VW Hyi was observed 42 times with *RXTE* between 1996 May 02 13:08 UT and 1996 May 16 23:55 UT (obsIDs 10041-02-01-00 through 10041-02-44-00 except 10041-02-31-00 and 10041-02-36-00), with a typical exposure of 2 ks each and separated by 4–16 hr. According to the AAVSO data base, VW Hyi went into an outburst around JD 2450201.0 (1996 Apr 27 at 12 UT), brightening from magnitude 13.5 to ~ 9 in about 6 hr, and returned to quiescence ($V > 13$) at about 2450216.25 (May 12 at 18 UT). Both the peak magnitude ($V < 9$) and the duration establish this as a superoutburst, even though we do not have direct confirmation through the detection of superhumps. Thus, the *RXTE* observations started ~ 5 d after the start of a superoutburst of VW Hyi and continued ~ 4 d after its return to quiescence.

WW Cet is a dwarf nova with a 4.22 hr orbital period, with an average quiescent magnitude of $V = 13.9$ and reaching $V \sim 11$ in outburst, and also showing occasional low states as faint as $V = 16.2$ (Ringwald et al. 1996). Hawkins et al. (1990) carried out radial velocity measurements of the accretion disk and the secondary, and assuming a main-sequence companion, estimated the white dwarf mass to be $0.83 \pm 0.16 M_{\odot}$ for this system. Recently, Simonsen & Stubbings (2011) have detected a standstill in WW Cet for the first time, establishing this to be a Z Cam type dwarf nova. However, at the time of our observations, it displayed the normal quiescence-outburst behavior of dwarf novae.

WW Cet was observed every day for 90 consecutive days between 2002 Aug 14 and 2002 Nov 11 (obsIDs 70005-01-01-00 through 70005-01-90-00), with a typical daily exposure of 2.5–3.5 ks. On 9 occasions, the observations were split into two sub-exposures (Oct 25, 26, 27, 29; Nov 1, 2, 3, 10, and 11), and once (Nov 8) into three sub-exposures, which were correspondingly shorter. Treating them separately, we therefore have 101 observations of WW Cet over a 3-month period. According to the AAVSO data base, WW Cet went into

outburst twice during this campaign; we will describe them in more details below. The last outburst before 2002 Aug 14 was poorly covered but appears to have ended on or around Jul 12; the first outburst after Nov 11 started on Dec 10.

We analyzed the standard 2 binned mode data (i.e., 129 channel spectra accumulated every 16 s) using HEASoft v6.6.3. We screened the data using the following screening criteria: angular separation between target and the pointing direction of $< 0.05^\circ$, elevation angle $> 5^\circ$, time since the last SAA passage of > 25 min, and electron contamination low (ELECTRON2 <0.1). PCA background was estimated using L7 faint model. VW Hyi observations were taken with 3 to 5 of the 5 PCUs active. Observations of WW Cet, on the other hand, were obtained with 2 or 3 active PCUs. This, however, included PCU0, which by 2002 had lost its propane layer, leading to a larger uncertainty in the background modeling. We therefore excluded PCU0 data from further analysis for WW Cet (but not for VW Hyi).

Since the PCA has little sensitivity below 2.5 keV, and these sources are not significantly detected above 10 keV, we analyze the background subtracted data in the 2.5–10 keV range. Since our main interest is the variability through an outburst or through an interoutburst period, our main data products are the average count rates per active PCU per pointing. We also performed spectral fitting for completeness, even though the data quality is rather limited for this purpose.

3. Results

3.1. VW Hyi

We present the X-ray and visual light curves of VW Hyi in Figure 1. There is a clear dichotomy in the observed *RXTE* count rates: the first 30 points (taken during the 10 day period covering the superoutburst peak and decline) are at $0.25 \pm 0.04 \text{ cs}^{-1}\text{PCU}^{-1}$ (mean and standard deviation). The last 12 points, taken after the return to quiescence, are at $0.67 \pm 0.08 \text{ cs}^{-1}\text{PCU}^{-1}$.

We have fitted the average quiescent spectra of VW Hyi using a single temperature *mekal* model (Mewe et al. 1985, 1986; Liedahl et al. 1995; Kaastra et al. 1996) with a Gaussian emission line at 6.4 keV and a neutral absorber. This gives an acceptable fit ($\chi^2_\nu=0.74$) with $kT = 6.4 \pm 1.3 \text{ keV}$, metallicity 0.44 ± 0.22 solar, and a 240 eV equivalent width line at 6.4 keV, and a 2–10 keV flux of $7.3 \times 10^{-12} \text{ erg cm}^{-2}\text{s}^{-1}$. Although multi-temperature models are more physical and known to be required in fitting higher-quality X-ray data on VW Hyi (Pandel et al. 2005) and result in even lower χ^2_ν with the *RXTE* data, they are not required due to the modest spectral resolution of the PCA.

We have also attempted spectral fits to the average superoutburst spectrum of VW Hyi for completeness. Although our analysis indicates a nominal 2–10 keV flux of 2.7×10^{-12} erg cm $^{-2}$ s $^{-1}$, this is below the confusion limit for the PCA data of 4×10^{-12} erg cm $^{-2}$ s $^{-1}$ (Jahoda et al. 2006) set by the Poissonian fluctuation in the cosmic X-ray background within the PCA field-of-view in the direction of VW Hyi. Therefore, while we can be confident that VW Hyi was fainter in superoutburst by 0.42 ± 0.09 cs $^{-1}$ PCU $^{-1}$ (approximately 5×10^{-12} erg cm $^{-2}$ s $^{-1}$) than in quiescence, we cannot determine the actual flux level or the spectral shape during superoutburst from our data.

The X-ray state transition took place in 17 hr. The last superoutburst obsID is 10041-02-30-00, with good exposure between 05:09 and 05:37 UT on 1996 May 12. The average 2.5–10 keV count rate is 0.20 cs $^{-1}$ and there is no significant change in brightness within the exposure. The first quiescence obsID is 10041-02-32-00¹, which started 21:10 UT on the same day, by which time it was already at 0.57 cs $^{-1}$. During this interval, VW Hyi declined from $V \sim 12.5$ (at 07:24 UT) to ~ 13.3 (at 18:37 UT), close to the quiescent level.

Our best-fit quiescent model predicts an *EXOSAT* ME rate of 0.6 cs $^{-1}$ per half array, which is in reasonable agreement with the observations of van der Woerd & Heise (1987). It also predicts ~ 3 cs $^{-1}$ with *Ginga* LAC, somewhat lower than the observed rate of ~ 5 cs $^{-1}$ of (Wheatley et al. 1996). This *Ginga* observation also included the outburst to quiescence transition. In this case, the strong variability within each orbit makes it harder to judge the exact duration of transition (see their Figure 2), but it was definitely shorter than 0.4 day, and was arguably as short as 0.1 day. In the latter interpretation, the last ~ 0.3 day of *Ginga* data may be interpreted as showing a slight rise from the initial quiescent level of ~ 4 cs $^{-1}$ to ~ 7 cs $^{-1}$ during some orbits.

3.2. WW Cet

We present the X-ray and visual light curves of WW Cet in Figure 2. Similarly to the case of VW Hyi, WW Cet shows a significant decrease in the X-ray flux level during the two outbursts. The average quiescent count rates and standard deviations are 0.65 ± 0.05 on Aug 14 & 15, 0.70 ± 0.07 during Aug 23–Oct 12, and 0.61 ± 0.12 during Aug 26–Nov 11. During outburst, the background-subtracted count rates are consistent with zero (0.00 ± 0.02 on Aug 17–21 and 0.00 ± 0.03), well within the systematic uncertainty in the background level.

¹It is likely that an obsID 10041-02-31-00 was planned between these exposures, but was canceled due to a higher priority observation.

The quiescent spectrum of WW Cet can be described using a single temperature model ($\chi^2_\nu=0.82$) with $kT = 7.0\pm0.5$ keV, metallicity 0.50 ± 0.10 solar, and a 67 eV equivalent width line at 6.4 keV, and a 2–10 keV flux of 8.2×10^{-12} erg cm $^{-2}$ s $^{-1}$. The quiescent flux is clearly not constant, but there is a sufficiently high level of point-to-point variability that we cannot comment on any systematic trends. Most importantly, we have fitted a constant and a linear line to the fully covered interoutburst period between Aug 23 and Oct 12. We obtain a lower χ^2_ν with the constant model: That is, we do not detect a secular trend in the quiescent X-ray flux of WW Cet.

We appear to have resolved the X-ray transitions into and out of outbursts in WW Cet. The count rates and statistical errors on Aug 16, Aug 22, Oct 13, and Oct 22 are 0.46 ± 0.04 , 0.41 ± 0.04 , 0.16 ± 0.04 , and 0.14 ± 0.04 , intermediate between the quiescent and outburst levels. We therefore investigate the relative timing of X-ray and optical transitions in more detail.

The Aug 16 X-ray data were taken between 13:17 and 14:11 UT. In the optical, AAVSO reports visible data on Aug 16 at 16:22 UT ($V=14.6$) and on Aug 17 at 12:30 UT ($V=11.2$). Thus, it appears that X-ray decline began before a significant rise in the optical. The intermediate X-ray point at the end of this outburst was taken on Aug 22 between 10:09 and 10:54 UT, which unfortunately falls in a significant gap in the optical coverage (between Aug 21 12:34 UT, when WW Cet was at $V=13.34$, and Aug 24 16:13 UT at $V=14.96$), but was in any case close to the return to quiescence. The Oct 13 X-ray data were taken between 13:27 and 14:21 UT. In the optical, WW Cet was already at $V=11.5$ at 10:15 UT. The Oct 25 X-ray data were taken between 20:00 and 20:13 UT, which is after it was seen at $V=15.3$ at 06:24 UT, therefore it appears that the X-ray recovery took place only after the system had already returned to quiescence.

3.3. Comparisons with Past Campaigns

In terms of the boundary layer behavior, the single best observed outburst of any dwarf novae may well be the 1996 October outburst of SS Cyg (Wheatley et al. 2003). This outburst had the following features: (1) During the rise of the outburst, the >2 (“hard”) keV flux initially increases (“enhancement – rise”); (2) The optically thick boundary layer develops, as evidenced by the sudden increase in the EUV flux and a simultaneous drop in the hard X-ray flux is delayed relative to the optical rise (“X-ray delay”); (3) Through the bulk of the outburst, the hard X-ray flux is lower than in quiescence (“X-ray suppression”); (4) During this period, the X-ray spectrum is softer than in quiescence (“Spectral softening”); (5) The optically thick boundary layer disappears near the end of the optical decay, as

evidenced by decreased EUV flux and increased hard X-ray flux (“Recovery at late decline”); and (6) The hard X-ray flux remains elevated for a period after the recovery (“Enhancement – decline”).

It is worth examining the body of data accumulated to date to determine if these features should be taken as the paradigm in which to interpret observations of outbursts of other dwarf novae, for which only lesser quantity and/or quality of data are available. We have therefore searched the literature for descriptions of well-observed outbursts, and judged how many of these features are shared by other outbursts.

SU UMa shares 4 of the 6 characteristics with SS Cyg according to Collins & Wheatley (2010), but failed to show X-ray enhancements at rise or in decline. In the case of VW Hyi, the X-rays are suppressed during outburst and recover at late decline. However, the *RXTE* campaign did not cover the rise, and the *ROSAT* data of Wheatley et al. (1996) suggest little or no X-ray delay. Hartmann et al. (1999) observed spectral softening in VW Hyi in outburst in their *BeppoSAX* data. However, elevated X-ray flux levels have not been definitively detected at rise or late decline, although the *Ginga* LAC data allow the possibility of enhancement at late decline. As for WW Cet, we arrive at the same set of answers as for VW Hyi based on the *RXTE* campaign. As for U Gem, the X-rays are in fact enhanced during outburst (Mattei et al. 2000), and the outburst spectral shape is complex enough to preclude a simple answer to the “softening” question (Güver et al. 2006). GW Lib is another dwarf nova with a higher X-ray flux during outburst (Byckling et al. 2009), which was also harder. We summarize these results in Table 1.

In addition, Szkody et al. (1999) contains an intriguing report that the hard X-ray flux may have recovered during the middle of two superoutbursts of V1159 Ori. However, the quality of the non-imaging *RXTE* data of V1159 Ori is rather low, so we have not included this object in our table. Similarly, while Verbunt et al. (1999) shows that the X-ray fluxes are suppressed during outburst in YZ Cnc, this campaign is less conclusive regarding other questions.

4. Discussion and Conclusions

This paper adds to the literature of X-ray observation of dwarf novae during outbursts. Through these observations and analyses, common, if not universal, patterns are emerging.

In the majority of dwarf novae, X-ray flux is suppressed during outburst. This is true of 4 out of 6 systems listed in Table 1, probably also true in YZ Cnc and (largely) in V1159 Ori, as well as other dwarf novae for which one or two X-ray spectra have been obtained

in outburst (e.g., Z Cam; see Baskill et al. 2001). We interpret this as the consequence of an optically thick boundary layer, which radiates most of the boundary layer luminosity during outburst. In these majority, the X-ray spectrum also appears to become softer in outburst. We propose Compton cooling as a possible mechanism for this, as Nelson et al. (2011) postulated for the quiescent X-ray emission from RS Oph.

Standard textbooks such as Frank et al. (2002) convincingly show that Compton cooling cannot be important in cataclysmic variables if the seed photons are from the heated surface of the white dwarf in a 1-zone accretion. However, the boundary layer in dwarf novae in outburst has at least two zones. At the equator, the boundary layer is optically thick, emitting copious soft photons; at somewhat higher latitude, the boundary layer is optically thin but subject to these external seed photons (see Figure 8 of Patterson & Raymond 1985a). Since the number of soft photons greatly exceeds that of the hot electrons (e.g., by a factor of 1,000 if the energy of a 10 keV electron is radiated away by 10 eV photons), each electron can experience many Compton scattering events even though each photon scatters once at most, thus keeping the soft spectrum largely unchanged (i.e., no hard inverse Compton component). Since the density of a cooling flow plasma rapidly increases towards lower temperatures, the optically thin region of the boundary layer is predominantly Compton cooled at high temperatures and predominantly Bremsstrahlung cooled at low temperatures. The observed soft-to-hard X-ray luminosity ratio for SS Cyg in outburst is ~ 40 (Wheatley et al. 2003), which makes it plausible that the optical thin part of the boundary layer is partly Compton-cooled, since the two emitting regions lie close to each other within the boundary layer.

To interpret the X-ray transitions, we must consider the disk instability model in more detail. The instability is principally a local property of the disk. However, once a transition from the quiescent state to the outburst state happens in one part of the disk, this propagates in the form of a heating front, behind which the mass inflow rate becomes much higher. X-ray behaviors are altered when the heating front reaches the inner edge of the disk. The optical flux, on the other hand, predominantly arises from the outer parts of the disk, which have the most emitting area. It is likely that the outburst can start at a variety of radial distances from the white dwarf in different systems or in different outbursts, and this is described as “outside-in” and “inside-out” outbursts in the studies of UV delay (see, e.g., Cannizzo et al. 1986). It is therefore possible to have a range of X-ray delay times among systems, and among different outbursts for a single dwarf nova. On the return to quiescence, the cooling front is likely to start from near the outer edge of the disk, and so X-ray transition happens when it reaches the boundary layer, near the end of optical decline.

From our own analysis and a survey of the literature, we conclude that the temporary

enhancement of X-ray flux during the rise and late decline has only been definitively seen in SS Cyg so far. There have only been two studies that attempt to incorporate the observational constraints imposed by the X-ray observations of dwarf novae throughout the course of an outburst into the disk instability model: The calculations of Schreiber et al. (2003) were specifically for SS Cyg, while those of Schreiber et al. (2004) were tailored for VW Hyi. These papers adopt a critical value of $\dot{M}_{\text{crit}} = 10^{16} \text{ g s}^{-1}$ in the inner disk as the dividing line between having an optically thin or thick boundary layer, following the empirical determination by Patterson & Raymond (1985b). A comparison of the theoretical X-ray fluxes shown in Fig. 4 of Schreiber et al. (2003) with those of Fig. 9 of Schreiber et al. (2004) shows the X-ray enhancements, both during rise and decline, to be common to both models. Thus, the model can account for the behavior exhibited by SS Cyg (see Fig. 2 of Wheatley et al. 2003), but not those of SU UMa, VW Hyi, or WW Cet (Table 1).

To investigate this further, we have derived the critical accretion rate observationally for the 6 systems listed in Table 1. We assume that the highest luminosity observed for the optically thin component reflects (or is close to) this critical value. We have collected the information in Table 2, including the adopted values and references for the distances and the white dwarf mass. We convert the bolometric X-ray luminosity to accretion rate using $L = GM_1\dot{m}/2R$, for a range of plausible values of M_1 . We also plot the results in Figure 3 against M_1 . For five systems, the plots are limited to the range of M_1 inferred from the reference cited. For SU UMa, we show three parallel lines over the entire mass range of the figure, as there are no published estimates for M_1 . The objects are color-coded based on the presence or otherwise of hard X-ray suppression and temporary rise. For comparison, we also plot the theoretical curves from Figure 8(a) of Popham & Narayan (1995).

Unfortunately, we are unable to reach a firm conclusion, except that the observationally derived values are all much lower than what Popham & Narayan (1995) predicted. This may not be a huge problem, since the specific values depend on the assumptions made in the study, including the adopted value for the viscosity parameter, α . The authors themselves caution against adopting these precise theoretical values, although the strong dependence on M_1 is likely to be a more robust conclusion. The values we derived observationally are in closer agreement with the empirical conclusion of Patterson & Raymond (1985b).

Nevertheless, we propose that the diversity of behavior shown by these 6 dwarf novae reflects the fact that \dot{M}_{crit} is in fact a function of various system parameters, and not uniform among all dwarf novae. In this view, the quiescent accretion rate is already close to this value in some systems, in which case any increase during outburst will immediately lead to the development of an optically thick boundary layer and hard X-ray suppression. Moreover, we propose that the primary mass is likely to be a key parameter, partly because the con-

version from luminosity to accretion rate depends on M_1 , and partly because the theoretical investigation by Popham & Narayan (1995) indicates that the critical rate depends steeply on M_1 .

Looking at individual systems, the inferred critical accretion rate for VW Hyi is extremely low, compared with those for other systems as well as theoretical expectations. We note, however, that the distance estimate for this system relies on an indirect argument without any indication of the size of the error bar, and should be refined. As for the two systems that do not show X-ray suppression during outburst, GW Lib can be understood as due to the extremely low accretion rate in quiescence (Hilton et al. 2007). Interestingly, the inferred accretion rate for U Gem is also low. If the current mass estimate is reliable, it also has the most massive white dwarf of the 6 systems, which suggests that the critical accretion rate is also highest. However, both these systems are reported to have developed an optically thick boundary layer, so the lack of hard X-ray suppression is a puzzle, particularly in light of our Compton-cooling interpretation for systems that do show hard X-ray suppression.

We believe that we should no longer assume a single critical accretion rate for all dwarf novae. Rather, we propose that future efforts be focused on determining which system parameters determine the critical accretion rate. Specifically, X-ray observations of more dwarf novae with well-determined distances and white dwarf masses should be obtained through outburst cycles. In particular, systems with extreme masses should be high priority targets, given the likely steep dependence of the critical accretion rate on the white dwarf mass.

This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA’s Goddard Space Flight Center. We acknowledge the planning effort by Drs. E. Schlegel and D. Baskill, who were the original PIs of VW Hyi and WW Cet observations, respectively. We also acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research.

REFERENCES

- Baskill, D.S., Wheatley, P.J. & Osborne, J.P., 2001, MNRAS, 328, 71
- Bitner, M.A., Robinson, E.L. & Behr, B.B., 2007, ApJ, 662 564
- Bradt, H.V., Rothschild, R.E. & Swank, J.H., 1993, A&AS, 97, 355
- Byckling, K., Osbornje, J.P., Wheatley, P.J., Wynn, G.A., Beardmore, A., Braitto, V., Mukai, K. & West, R.G., 2009, MNRAS, 399, 1576
- Byckling, K., Mukai, K., Thorstensen, J.R. & Osborne, J.P., 2010, MNRAS, in press
- Cannizzo, J.K., Wheeler, J.C. & Polidan, R.S., 1986, ApJ, 301, 634
- Collins, D.J. & Wheatley, P.J., 2010, MNRAS, 402, 1816
- Echevarria, J., de la Fuente, E. & Costero, R., 2007, AJ, 134, 262
- Frank, J., King, A. & Raine, D.J., 2002, “Accretion Power in Astrophysics: Third Edition” (Cambridge University Press)
- Güver, T., Uluayazi, C., Özkan, M.T. & Göğüs, E., 2006, MNRAS, 372, 450
- Harison, T.E., Johnson, J.J., McArthur, B.E., Benedict, G.F., Szkody, P., Howell, S.B. & Gelnio, D.M. 2004, AJ, 127, 460
- Hartmann, H.W., Wheatley, P.J., Heise, J., Mattei, J.A. & Verbunt, F., 1999, A&A, 349, 588
- Hawkins, N.A., Smith, R.C. & Jones, D.H.P. 1990, “Accretion-powered Compact Binaries,” ed. Mauche, C.W., Cambridge University Press, p113
- Hilton, E.J., Szkody, P., Mukadam, A., Mukai, K., Hellier, C., van Zyl, L. & Homer, L., 2007, AJ, 134, 1503
- Jahoda, K., Swank, J.H., Giles, A.B., Stark, M.J., Strohmayer, T., Zhang, W. & Morgan, E.H., 1996, in EUV, X-ray and Gamma-Ray Instrumentation for Astronomy VII, ed O.H. Siegmund (Bellingham, WA: SPIE), 59
- Jahoda, K., Markwardt, C.B., Radeva, Y., Rots, A.H., Stark, M.J., Swank, J.H., Strohmayer, T.E. & Zhang, W., 2006, ApJS, 163, 401

- Kaastra, J. S., Mewe, R., & Nieuwenhuijzen, H., 1996, in “UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas,” Eds. K. Yamashita & T. Watanabe, Tokyo: Universal Academy Press, 1996, 411
- Lasota, J.-P., 2001, *New Astronomy Reviews*, 45, 449
- Liedahl, D. A., Osterheld, A. L., & Goldstein, W. H., 1995, *ApJ*, 438, L115
- Mattei, J.A., Mauche, C. & Wheatley, P.J., 2000, *JAAVSO*, 28, 160
- Mewe, R., Gronenschild, E. H. B. M., & van den Oord, G. H. J., 1985, *A&AS*, 62, 197
- Mewe, R., Lemen, J. R., & van den Oord, G. H. J., 1986, *A&AS*, 65, 511
- Meyer, F. & Meyer-Hofmeister, E., 1994, *A&A*, 288, 175
- Nelson, T., Mukai, K., Orio, M., Luna, G. & Sokoloski, J., 2011, *ApJ*, in press (astro-ph/1105.2569)
- Pandel, D., Córdova, F.A., Mason, K.O. & Priedhorsky, W.C., 2005, *ApJ*, 626, 396
- Patterson, J. & Raymond, J.C., 1985, *ApJ*, 292, 535
- Patterson, J. & Raymond, J.C., 1985, *ApJ*, 292, 550
- Popham, R. & Narayan, R., 1995, *ApJ*, 442, 337
- Pringle, J.E., Bateson, F.M., Hassall, B.J.M., Heise, J., van der Woerd, H., Holberg, J.B., Polidan, R.S., van Amerongen, S., van Paradijs, J. & Verbunt, F., 1987, *MNRAS*, 225, 73
- Ringwald, F.A., Thorstensen, J.R., Honeycutt, R.K. & Smith, R.C., 1996, *AJ*, 111, 2077
- Schoembs, R. & Vogt, N., 1981, *A&A*, 97, 185
- Schreiber, M.R., Hameury, J.-M. & Lasota, J.-P., 2003, *A&A*, 410, 239
- Schreiber, M.R., Hameury, J.-M. & Lasota, J.-P., 2004, *A&A*, 427, 621
- Simonsen, M. & Stubbings, R., 2011, *JAAVSO*, in press (astro-ph/1012.1545)
- Smith, A.J., Haswell, C.A. & Hynes, R.L., 2006, *MNRAS*, 369, 1537
- Sproats, L.N., Howell, S.B. & Mason, K.O., 1996, *MNRAS*, 282, 1211

- Szkody, P., Linnell, A., Honeycutt, K., Robertson, J., Silber, A., Hoard, D.W., Pastwick, L., Desai, V., Hubeny, I., Cannizzo, J., Liller, W., Zissell, R. & Walker, G., 1999, *ApJ*, 521, 362
- Thorstensen, J.R., 2003, *AJ*, 126, 3017
- van der Woerd, H. & Heise, J., 1987, *MNRAS*, 225, 141
- van Spaandonk, L., Steeghs, D., Marsh, T.R. & Parsons, S.G., 2010, *ApJ*, 715, L10
- Verbunt, F., Wheatley, P.J. & Mattei, J.A., 1999, *A&A*, 346, 146
- Warner, B., 1987, *MNRAS*, 227, 23
- Wheatley, P.J. & West, R.G., 2003, *MNRAS*, 345, 1009
- Wheatley, P.J., Verbunt, F., Belloni, T., Watson, M.G., Naylor, T. & Ishida, M., 1996, *A&A*, 307, 137
- Wheatley, P.J., Mauche, C.W. & Mattei, J.A., 2003, *MNRAS*, 345, 49

Table 1. The SS Cygni Paradigm

Object	X-ray Suppression	Spectral Softening	X-ray Delay	Recovery at late Decline	Enhancement – Rise	Enhancement – Decline
SS Cyg	Yes	Yes	Yes	Yes	Yes	Yes
SU UMa	Yes	Yes	Yes	Yes	No	No
VW Hyi	Yes	Yes	No?	Yes	No	Maybe
WW Cet	Yes	?	No?	Yes	No	No
U Gem	No	?	Yes	Yes	?	?
GW Lib	No	No	?	?	?	?

Table 2. Critical Mass Accretion Rate

Object	Distance ^a (pc)	Primary Mass ^b (M _⊙)	L _{X,peak} ^c (erg s ⁻¹)	\dot{m} g s ⁻¹	Fiducial M ₁ M _⊙
SS Cyg	165 ⁺¹³ ₋₁₁	0.81±0.19	1.2×10 ³³	1.0×10 ¹⁶	1.0
SU UMa	260 ⁺¹⁹⁰ ₋₉₀		2.6×10 ³²	4.2×10 ¹⁵	0.75
VW Hyi	65	0.71 ^{+0.18} _{-0.26}	8.1 ×10 ³⁰	1.3×10 ¹⁴	0.71
WW Cet	146±25	0.83±0.16	1.1 ×10 ³²	1.3×10 ¹⁵	0.83
U Gem	100±4	1.20±0.05	1.4 ×10 ³²	7.3×10 ¹⁴	1.20
GW Lib	104 ⁺³⁰ ₋₂₀	0.84±0.02	8.4×10 ³²	7.0 ×10 ¹⁵	1.0

^aDistances are taken from Harrison et al. (2004) for SS Cyg and U Gem, Thorstensen (2003) for SU UMa and GW Lib, Warner (1987) for VW Hyi, and Sproats et al. (1996) for WW Cet.

^bThe white dwarf masses are taken from Bitner et al. (2007) for SS Cyg, Smith et al. (2006) for VW Hyi, Echevarria et al. (2007) for U Gem, and van Spaandonk et al. (2010) for GW Lib. There is no estimate in the literature for SU UMa, while the numbers for WW Cet uses the mass ratio obtained by Hawkins et al. (1990) and assumes a main-sequence secondary.

^cThe peak X-ray luminosities are taken from ? for SS Cyg, Collins & Wheatley (2010) for SU UMa, Pandel et al. (2005) for VW Hyi and WW Cet, Güver et al. (2006) for U Gem and (Byckling et al. 2010) for GW Lib. These values are then used by the same authors to infer the highest accretion rate through the optically thin boundary layer for the fiducial white dwarf mass.

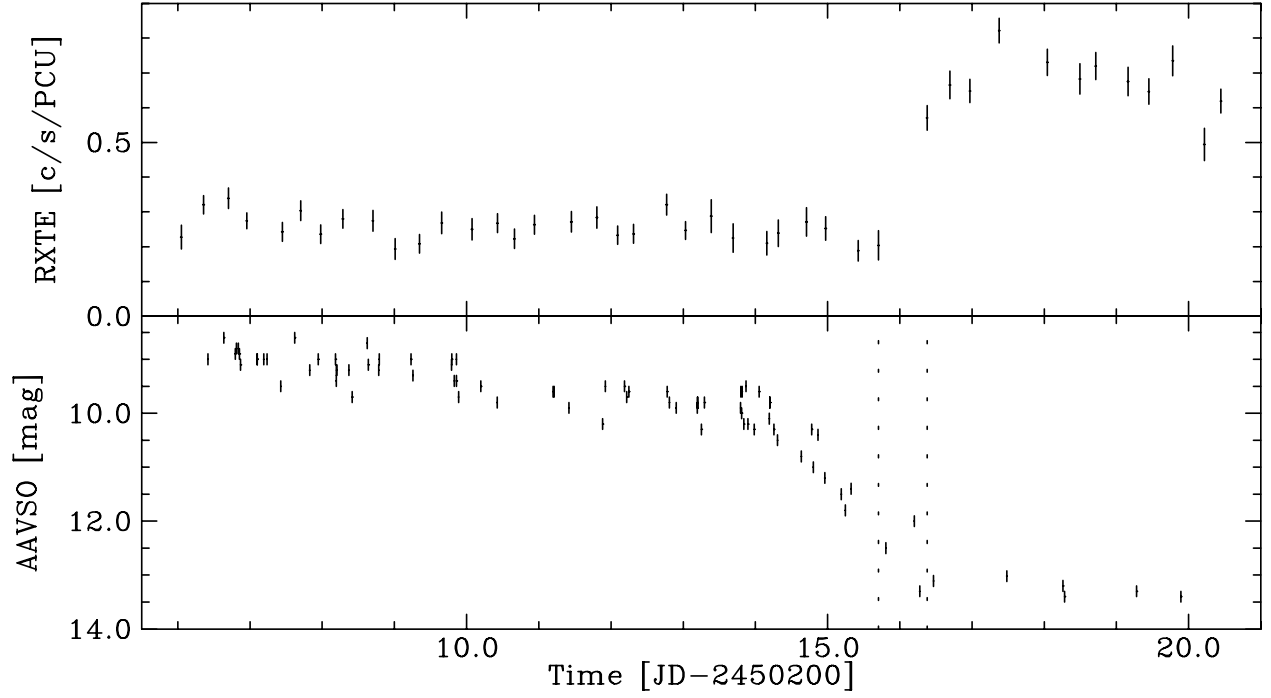


Fig. 1.— The X-ray (top panel) and visual (bottom) light curves of VW Hyi during 1996 May. The X-ray data were obtained with *RXTE* PCA while the optical data were collected by amateur observers and compiled by AAVSO. Two vertical dashed lines mark the time of the last “outburst” and the first “quiescent” X-ray points (see text).

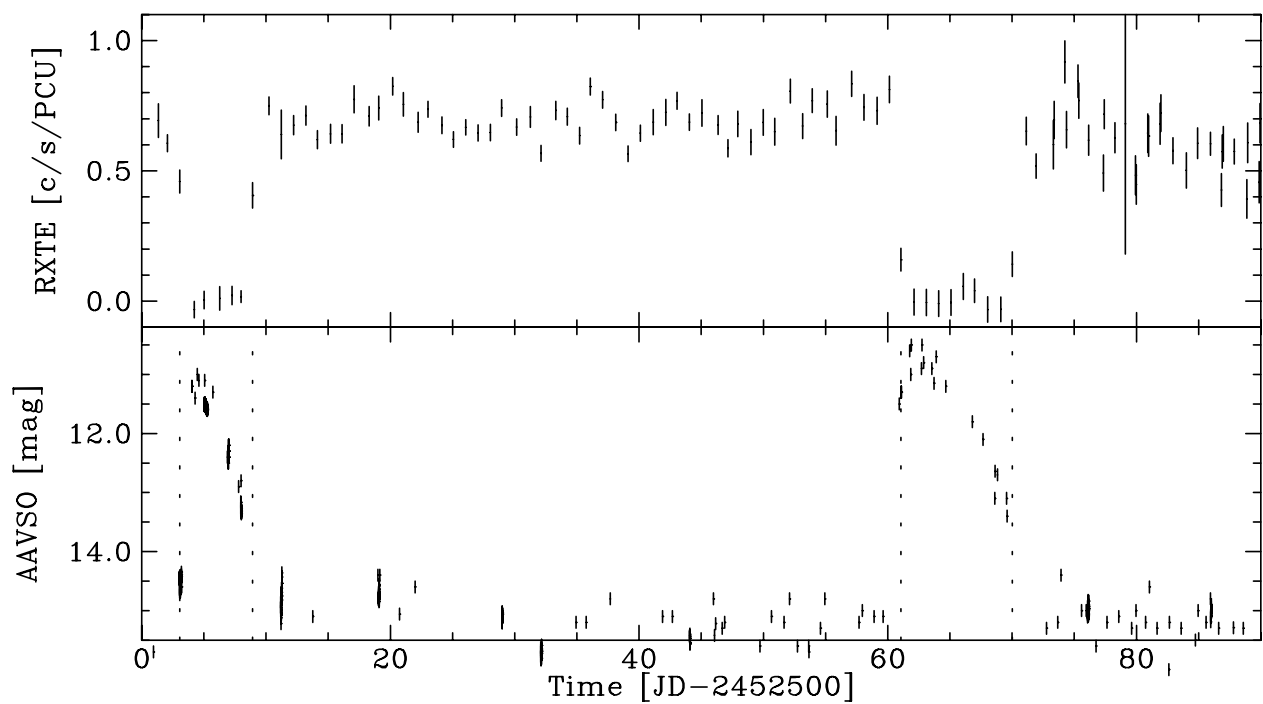


Fig. 2.— The X-ray (top panel) and visual (bottom) light curves of WW Cet during 2002 Aug–Nov. The X-ray data were obtained with *RXTE* PCA while the optical data were collected by amateur observers and compiled by AAVSO.

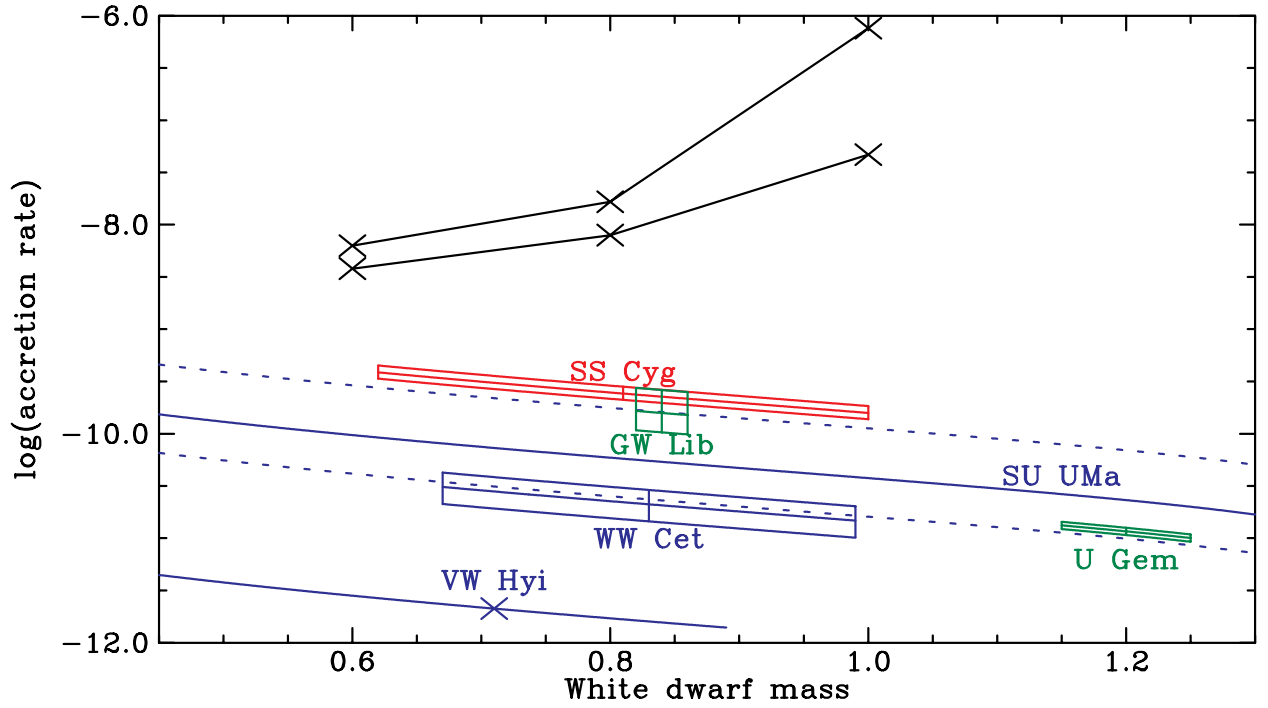


Fig. 3.— The inferred accretion rate at the highest flux of the optically thin X-ray emission, plotted against the white dwarf mass (see text for object-by-object details). Also shown are the theoretical curves of optically thin-to-thick transition from Popham & Narayan (1995).